

OPTICAL IMAGING SYSTEM

BACKGROUND OF THE INVENTION

1. Field of the Invention

5 The present invention relates to an optical imaging system used in an image transmission portion of, e.g., a facsimile device or a copier. More particularly, the present invention relates to an optical imaging system including a plurality of rod lenses arranged in an array.

10 2. Description of the Related Art

Optical imaging systems including a plurality of rod lenses with a refractive index distribution in the radial direction that are arranged in an array are widely used in the image transmission portion of, e.g., facsimile devices or copiers.

15 The refractive index distribution of such rod lenses can be expressed, e.g., by

$$Eq. 6 \quad n(r)^2 = n_0^2 \cdot \{1 - (g \cdot r)^2 + h_4 \cdot (g \cdot r)^4 + h_6 \cdot (g \cdot r)^6 + h_8 \cdot (g \cdot r)^8\}$$

20 where r is a radial distance from the optical axis of the rod lens, $n(r)$ is a refractive index at the radial distance r , n_0 is a refractive index on the optical axis of the rod lens (i.e., the center refractive index), and g , h_4 , h_6 and h_8 are refractive index distribution coefficients.

Conventionally, the resolving power demanded from such a rod lens array called for an MTF (modulation transfer function) of at least 60% when a pattern of 4 - 6 line-pairs/mm (ca. 200 dpi - 300 dpi) was imaged. To meet this demand, it was sufficient to control only g or both g and h_4 of the refractive index distribution coefficients for the rod lenses.

30 Recently, however, with the steadily rising quality of printers and scanners, there is a demand for rod lens arrays with a resolving power of at least 12 line-pairs/mm (ca. 600 dpi). To achieve a rod lens array having such a high resolving power, all the refractive index distribution coefficients, including h_6 and h_8 , have to be controlled precisely during design and fabrication of the rod lens array.

35 It is possible to determine the optimum refractive index distribution coefficients for correcting the spherical aberration on the optical axis of a single rod lens. However, in the case of a plurality of rod lenses arranged

in an array, a change in the resolving power may be caused not only by the spherical aberration, field curvature and astigmatism of the individual lenses but also by the overlapping of images from neighboring lenses.

The optimum refractive index distribution also changes depending on the brightness of the rod lenses. For example, when bright rod lenses having a large angular aperture are employed, the refractive index distribution coefficients for a small axial spherical aberration are very different from the refractive index distribution coefficients for a small field curvature. The best resolving power can be achieved by striking a balance between the two.

An overlapping degree m is given by

Eq. 7 $m = X_0/2r_0$

where r_0 is the radius of an effective lens portion, i.e., the radius of the portion of each rod lens that functions as a lens, and X_0 is the image radius that a single rod lens projects onto an image plane (i.e., the field of view). Here, X_0 is defined as $X_0 = -r_0/\cos(Z_0\pi/P)$, where Z_0 is the length of a rod lens and P is a one-pitch length of the rod lens. Even if the rod lenses have the same refractive index distribution, the overlapping degree m changes with the lens length, and thus causing a change in the resolving power.

Consequently, to achieve a high resolving power, the refractive index distribution coefficients have to be determined separately in accordance with at least the brightness and the overlapping degree of each rod lens.

SUMMARY OF THE INVENTION

Therefore, with the foregoing in mind, it is an object of the present invention to provide an optical imaging system including a plurality of rod lenses arranged in an array and having a refractive index distribution that is ideal for achieving a high resolving power.

An optical imaging system according to a configuration of the present invention includes a rod lens array including a plurality of rod lenses having a refractive index distribution in the radial direction that are arranged in two rows with their optical axes in parallel, and a manuscript plane and an image plane that are located on the opposite sides of the rod lens array. The refractive index distribution of the rod lenses is expressed by

$$\text{Eq. 8} \quad n(r)^2 = n_0^2 \cdot \{1 - (g \cdot r)^2 + h_4 \cdot (g \cdot r)^4 + h_6 \cdot (g \cdot r)^6 + h_8 \cdot (g \cdot r)^8\}$$

where r is a radial distance from the optical axis of the rod lenses, n_0 is a refractive index on the optical axis of the rod lenses, and g , h_4 , h_6 and h_8 are refractive index distribution coefficients. The refractive index distribution coefficients h_4 , h_6 and h_8 are on a spheroid in a Cartesian coordinate system with h_4 being x-axis, h_6 being y-axis and h_8 being z-axis. The spheroid is defined by a vector X^* that is expressed by

$$\text{Eq. 9} \quad X^* = (x, y, z) = O^* + k_A A^* + k_B B^* + k_C C^*$$

where O^* is a vector from the origin of the Cartesian coordinate system to the center of the spheroid, A^* , B^* and C^* are vectors in the directions of the major axis, the mean axis and the minor axis of the spheroid, respectively, and k_A , k_B and k_C satisfy $k_A^2 + k_B^2 + k_C^2 \leq 1$.

According to this configuration, an optical imaging system can be provided that includes a plurality of rod lenses arranged in an array and has the optimum refractive index distribution for attaining a high resolving power of at least 12 line-pairs/mm (ca. 600 dpi) when the outer diameter of the lenses is 0.6 mm.

In the optical imaging system according to the configuration of the present invention, it is preferable that k_A , k_B and k_C satisfy

$$\text{Eq. 10} \quad k_A^2 + k_B^2 + k_C^2 \leq 0.7.$$

This preferred example can provide an optical imaging system having a more favorable refractive index distribution.

In the optical imaging system according to the configuration of the present invention, it is preferable that the refractive index n_0 on the optical axis of the rod lenses is in the range of $1.4 \leq n_0 \leq 1.8$.

In the optical imaging system according to the configuration of the present invention, it is preferable that the product $g \cdot r_0$ of the refractive index distribution coefficient g and a radius r_0 of the portion of each rod lens functioning as a lens is in the range of $0.04 \leq g \cdot r_0 \leq 0.27$. When $g \cdot r_0$ is smaller than 0.04, the image may become too dark and the time for scanning etc. is long. When $g \cdot r_0$ is larger than 0.27, the influence of field

curvature and astigmatism may become too large and the resolving power is reduced.

In the optical imaging system according to the configuration of the present invention, it is preferable that the refractive index distribution of the rod lenses is expressed by

$$Eq. 11 \quad n(r)^2 = n_0^2 \cdot \{1 - (g \cdot r)^2 + f(r)\}$$

where $f(r)$ is a function of r , and that the $f(r)$ satisfies

$$Eq. 12 \quad h_{4A} \cdot (g \cdot r)^4 + h_{6A} \cdot (g \cdot r)^6 + h_{8A} \cdot (g \cdot r)^8 \leq f(r) \leq h_{4B} \cdot (g \cdot r)^4 + h_{6B} \cdot (g \cdot r)^6 + h_{8B} \cdot (g \cdot r)^8$$

for r in the range of $0 \leq r \leq r_0$ (r_0 : a radius of the portion of each rod lens functioning as a lens) with respect to two groups of refractive index distribution coefficients ($n_0, g, h_{4A}, h_{6A}, h_{8A}$) and ($n_0, g, h_{4B}, h_{6B}, h_{8B}$) that are in the ranges determined by Equation 9.

In the optical imaging system according to the configuration of the present invention, it is preferable that the radius r_0 of the portion of each rod lens functioning as a lens is in the range of $0.05 \text{ mm} \leq r_0 \leq 0.60 \text{ mm}$. This preferred example can facilitate production and assembly of the rod lenses and suppress the aberrations of the rod lens array significantly.

The refractive index distribution at the peripheral portion of each rod lens can differ considerably from the designed value. Therefore, in many cases, this portion cannot be used as a lens. Also, the lenses may include a light absorption layer to prevent stray light caused by total reflection at the lens side surface. Moreover, depending on the conditions for fabricating the rod lens array, the rod lenses may be arranged at a certain distance between each other. Thus, in the optical imaging system according to the configuration of the present invention, it is preferable that r_0/R is in the range of $0.5 \leq r_0/R \leq 1.0$, where r_0 is the radius of the portion of each rod lens functioning as a lens and $2R$ is a distance between the optical axes of two neighboring rod lenses.

In the optical imaging system according to the configuration of the present invention, it is preferable that Z_0/P is in the range of $0.5 \leq Z_0/P \leq 1.0$, where Z_0 is the length of the rod lenses and $P = 2\pi/g$ is a one-pitch length of the rod lenses. This preferred example can produce an erected image.

In the optical imaging system according to the configuration of the present invention, it is preferable that an overlapping degree m is in the range of $0.9 \leq m \leq 5.0$, and the overlapping degree m is given by $m = X_0/2r_0$, where r_0 is the radius of the portion of each rod lens functioning as a lens and X_0 is an image radius that the rod lens projects onto the image plane. When the overlapping degree m is larger than 5.0, the image may become too dark and the time for scanning etc. is long. When the overlapping degree m is smaller than 0.9, the periodic irregularity in brightness of the image plane is increased.

In the optical imaging system according to the configuration of the present invention, it is preferable that a parallel plane transparent substrate is arranged so that the manuscript plane is located at the front focal position of the rod lens array. This preferred example allows the manuscript plane to be set at the front focal position by only pressing a manuscript to the surface of the transparent substrate. Moreover, it is preferable that the parallel plane transparent substrate is in contact with the lens surface of the rod lens array. This can be achieved easily by adjusting the thickness of the transparent substrate. This preferred example can simplify adjustment of the distance between the rod lens array and the front focal position during fabrication of the optical imaging system, thereby reducing the cost.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view showing a rod lens used in an optical imaging system according to an embodiment of the present invention.

FIG. 2 is a perspective view showing an optical imaging system according to an embodiment of the present invention.

FIG. 3 is a graph of the refractive index distribution of the rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 4 is a schematic view showing the image formation by a rod lens used in an optical imaging system according to an embodiment of the present invention.

FIG. 5 is a schematic view showing the image composition by a plurality of rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 6 is a schematic view showing the measurement point of the

MTF value of an optical imaging system according to an embodiment of the present invention.

FIG. 7 shows a "good image range" for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 8 shows the dependency of x_0 upon an overlapping degree m that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 9 shows the dependency of y_0 upon x_0 that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 10 shows the dependency of z_0 upon y_0 that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 11 shows the dependency of A_x upon m/θ that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 12 shows the dependency of A_x upon θ that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 13 shows the dependency of $\log_{10}(-A_y)$ upon $(A_x + 2m)$ and that of $\log_{10}A_z$ upon $(A_x + 2m)$, each of which determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 14 shows the dependency of B_x upon A_x that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an embodiment of the present invention.

FIG. 15 shows the dependency of B_y upon A_x that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an

embodiment of the present invention.

FIG. 16 shows the dependency of B_z upon A_x that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an
5 embodiment of the present invention.

FIG. 17 shows the dependency of p upon x_0 that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an
10 embodiment of the present invention.

FIG. 18 shows the dependency of q upon x_0 that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an
15 embodiment of the present invention.

FIG. 19 shows the dependency of s upon x_0 that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an
20 embodiment of the present invention.

FIG. 20 shows the dependency of $|C^*|$ upon $|A^*| \cdot m^2$ that determines the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system
25 according to an embodiment of the present invention.

FIG. 21 is a cross-sectional view showing an optical imaging system provided with a parallel plane transparent substrate according to an
30 embodiment of the present invention.

FIG. 22 shows another way of determining the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 of the rod lenses used in an optical imaging system according to an embodiment of the
35 present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Hereinafter, the present invention will be described more specifically by way of an embodiment.

As shown in FIGS. 1 and 2, this embodiment employs a rod lens array 2 for one-to-one imaging, where a plurality of columnar rod lenses 1
35 having a refractive index distribution in the radial direction are arranged in two rows with their optical axes 1a in parallel. A manuscript plane 3 and an image plane 4 are located on the opposite sides of the rod lens array 2,

thus providing an optical imaging system.

As shown in FIG. 3, the refractive index n of the rod lenses 1 is distributed in the radial direction, which is expressed by

$$Eq. 13 \quad n(r)^2 = n_0^2 \cdot \{1 - (g \cdot r)^2 + h_4 \cdot (g \cdot r)^4 + h_6 \cdot (g \cdot r)^6 + h_8 \cdot (g \cdot r)^8\}$$

where r is a radial distance from the optical axis 1a of the rod lens 1, $n(r)$ is the refractive index at the radial distance r , n_0 is the refractive index on the optical axis 1a of the rod lens 1 (i.e., the center refractive index), and g , h_4 , h_6 and h_8 are refractive index distribution coefficients.

To achieve erected images as shown in FIG. 4, the ratio Z_0/P of a length Z_0 of the rod lenses 1 and a one-pitch length $P = 2\pi/g$ of the rod lenses 1 has to be in the range of $0.5 \leq Z_0/P \leq 1.0$.

The distance L_0 between the end surface (lens surface) of the rod lens array 2 and the manuscript plane 3 and that between the end surface (lens surface) of the rod lens array 2 and the image plane 4 (see FIG. 2) are expressed by

$$Eq. 14 \quad L_0 = -\{1/(n_0 \cdot g)\} \cdot \tan(Z_0\pi/P).$$

It is desirable that the radius r_0 of the effective lens portion, i.e., the radius of the portion of each rod lens 1 that functions as a lens, is in the range of $0.05 \text{ mm} \leq r_0 \leq 0.60 \text{ mm}$.

Lenses having a small r_0 can provide high resolution more easily because the amount of blurred image caused by various aberrations of the rod lenses 1 increases in proportion to the size of the entire lens. However, when r_0 is smaller than 0.05 mm , it is difficult to produce and assemble those rod lenses 1. When the radius r_0 of the effective lens portion of each rod lens 1 is larger than 0.60 mm , the aberrations of the rod lens array 2 become too large.

The obtainable value of the refractive index n_0 on the optical axis 1a of the rod lens 1 (i.e., the center refractive index) depends on the rod lens material (glass or synthetic resin) and is in the range of $1.4 \leq n_0 \leq 1.8$.

The brightness of the rod lenses 1 depends on the dimensionless factor $g \cdot r_0$ or an angular aperture that indicates the range over which the lenses can accept light. The angular aperture θ ($^\circ$) is expressed by

$$\text{Eq. 15 } \theta = (n_0 \cdot g \cdot r_0) / (\pi/180).$$

It is desirable that the dimensionless factor $g \cdot r_0$ is in the range of $0.04 \leq g \cdot r_0 \leq 0.27$. When $g \cdot r_0$ is smaller than 0.04, the image may become too dark and the time for scanning etc. is long. When $g \cdot r_0$ is larger than 0.27, the influence of field curvature and astigmatism may become too large and the resolving power is reduced.

The desirable range of $g \cdot r_0$ corresponds to $4^\circ \leq \theta \leq 24^\circ$, e.g., when the center refractive index n_0 is 1.60.

In an optical imaging system including the above rod lens array 2, a compound image is formed by a plurality of rod lenses 1 on the image plane 4, as shown in FIG. 5. Therefore, it is convenient to use a dimensionless factor that represents the amount of overlap, i.e., a so-called "overlapping degree". This overlapping degree m is expressed by

$$\text{Eq. 16 } m = X_0/2r_0$$

where X_0 is the image radius (field of view) that the single rod lens 1 projects onto the image plane 4 and is defined by $X_0 = -r_0/\cos(Z_0\pi/P)$.

It is desirable that the overlapping degree m of the rod lens array 2 is in the range of $0.9 \leq m \leq 5.0$. When the overlapping degree m is larger than 5.0, the image may become too dark and the time for scanning etc. is long. When the overlapping degree m is smaller than 0.9, the periodic irregularity in brightness of the image plane 4 is increased.

It is most desirable to match the distance $2R$ between the optical axes of neighboring rod lenses 1 with $2r_0$ (i.e., a diameter of the effective lens portion of each rod lens 1). This is because the largest quantity of light can be focused on the image. However, the refractive index distribution at the peripheral portion of the rod lens 1 can differ considerably from the designed value. Therefore, in many cases, this portion cannot be used as a lens. Also, the lenses may include a light absorption layer to prevent stray light caused by total reflection at the lens side surface. Moreover, depending on the conditions for fabricating the rod lens array 2, the rod lenses 1 may be arranged with a certain distance between each other. Considering the above circumstances, the ratio r_0/R may be set so as to be in the range of $0.5 \leq r_0/R \leq 1.0$.

When developing the present invention, the inventors took the

standard for "high resolution" to mean "a value of at least 50% for the MTF of a 24 line-pairs/mm pattern on the center line of a rod lens array 2 including a plurality of rod lenses 1, which have an effective lens portion radius r_0 of 0.15 mm and are arranged in two rows with their optical axes 1a in parallel", and determined the refractive index distribution coefficients h_4 , h_6 and h_8 that satisfy this standard.

Specifically, a rod lens array 2 having the above configuration was designed. Ray tracing was performed by taking the perpendicular projection of a point A as indicated in FIG. 6 onto the object plane for the light source. The MTF values of a 24 line-pairs/mm pattern were calculated for the X direction and for the Y direction, and the smaller value was taken as the MTF value for the rod lens array 2. The optical design software "Olso Six" by Sinclair Optics (US) was used for the ray tracing. Table 1 shows the specifications of twenty-four types of rod lens arrays 2 used for the calculation. The angular aperture θ ranges from 7 to 20°, the center refractive index n_0 of the rod lenses 1 ranges from 1.5 to 1.8, the overlapping degree m ranges from 1.0 to 2.5, and the radius r_0 of the portion of each rod lens 1 that functions as a lens is set to 0.3 mm. For each of the rod lens arrays 2, a range of the refractive index distribution coefficients h_4 , h_6 and h_8 over which the MTF value of a 24 line-pairs/mm pattern is at least 50% was determined. Hereinafter, this range is referred to as "good image range" of the refractive index distribution coefficients h_4 , h_6 and h_8 .

TABLE 1

No.	$\theta(^{\circ})$	n_0	$r_0(\text{mm})$	m
1	18.00	1.65	0.3	1.0
2	18.00	1.65	0.3	1.5
3	18.00	1.65	0.3	2.0
4	18.00	1.65	0.3	2.5
5	12.00	1.65	0.3	1.0
6	12.00	1.65	0.3	1.5
7	12.00	1.65	0.3	2.0
8	12.00	1.65	0.3	2.5
9	8.00	1.65	0.3	1.0
10	8.00	1.65	0.3	1.5
11	8.00	1.65	0.3	2.0
12	8.00	1.65	0.3	2.5
13	19.70	1.80	0.3	1.0
14	19.70	1.80	0.3	2.5
15	16.32	1.50	0.3	1.0
16	16.32	1.50	0.3	2.5
17	13.11	1.80	0.3	1.0
18	13.11	1.80	0.3	2.5
19	10.90	1.50	0.3	1.0
20	10.90	1.50	0.3	2.5
21	8.73	1.80	0.3	1.0
22	8.73	1.80	0.3	2.5
23	7.27	1.50	0.3	1.0
24	7.27	1.50	0.3	2.5

Under any of the conditions shown in Table 1, a vector X^* (hereinafter, vectors are accompanied by " $*$ ") that represents the good image range can be described as a long and narrow spheroid in a Cartesian coordinate system with h_4 being x-axis, h_6 being y-axis and h_8 being z-axis, as shown in FIG. 7. Since FIG. 7 is a schematic view, the dimensions of the axes, the position and shape of the spheroid, or the like do not correspond to the specific values of the good image range, which will be described below.

The vector X^* is expressed by

$$\text{Eq. 17 } X^* = (x, y, z) = O^* + k_A A^* + k_B B^* + k_C C^*$$

where k_A , k_B and k_C are the constants that satisfy the relationship given by

$$\text{Eq. 18 } k_A^2 + k_B^2 + k_C^2 \leq 1,$$

5 O^* is a vector from the origin of the Cartesian coordinate system to the center of the spheroid, and A^* , B^* and C^* are vectors in the directions of the major axis, the mean axis (intermediate axis) and the minor axis of the spheroid, respectively. The vector O^* is referred to as "center vector", and the vectors A^* , B^* and C^* are referred to as "major vector", "mean vector" and "minor vector" in the following description.

10 The good image range can be determined by these vectors O^* , A^* , B^* and C^* , each of which depends on the characteristic parameters of the lenses, such as the angular aperture θ , the center refractive index n_0 , and the overlapping degree m . The relationship between the vectors and the characteristic parameters will be described below.

(1) Center vector O^*

15 The components of the center vector O^* on the x-axis, y-axis and z-axis can be represented by x_0 , y_0 and z_0 , respectively. That is, the center vector O^* is expressed by

Eq. 19 $O^* = (x_0, y_0, z_0).$

20 The dependency of each component upon the characteristic parameters of the lenses is determined by simulation.

FIG. 8 shows the dependency of x_0 upon the overlapping degree m , which is calculated for the rod lens arrays 2 appropriately selected from Table 1. As shown in FIG. 8, an approximate line is determined based on the calculated values and expressed by

Eq. 20 $x_0 = -1.3m + 3.3.$

30 FIG. 9 shows the dependency of y_0 upon x_0 , which is calculated for the rod lens arrays 2 appropriately selected from Table 1. Taking the deviation from a linear relationship between the two components into consideration, the dependency can be approximated by

Eq. 21 $y_0 = -80x_0 + 16(m - 2.6)(10 - \theta \cdot n_0)^2 + 100.$

35 Substitution of x_0 from Equation 20 into Equation 21 yields an approximate value of y_0 , represented by a white dot in FIG. 9. As can be

seen from FIG. 9, these approximate values agree well with the exactly calculated values of y_0 .

FIG. 10 shows the dependency of z_0 upon y_0 , which is calculated for the rod lens arrays 2 appropriately selected from Table 1. Taking the deviation from a linear relationship between the two components into consideration, the dependency can be approximated by

$$Eq. 22 \quad z_0 = -100y_0 + 15000m - 150000n_0 + 230000.$$

Substitution of the approximate value of y_0 , which has been obtained by substituting x_0 from Equation 20 into Equation 21, into Equation 22 yields an approximate value of z_0 , represented by a white dot in FIG. 10. As can be seen from FIG. 10, these approximate values agree well with the exactly calculated values of z_0 .

(2) Major vector A^*

The components of the major vector A^* on the x-axis, y-axis and z-axis can be represented by A_x , A_y and A_z , respectively. That is, the major vector A^* is expressed by

$$Eq. 23 \quad A^* = (A_x, A_y, A_z).$$

FIG. 11 shows the dependency of A_x upon m/θ . Here, among the twenty-four types of rod lens arrays 2 in Table 1, the dependency is calculated for three to four types of rod lens arrays 2 having the same angular aperture θ and different overlapping degrees m when the angular aperture is 8° , 12° and 18° , respectively. As can be seen from FIG. 11, the dependency for each angular aperture θ can be approximated by a straight line. The approximation is expressed by

$$Eq. 24 \quad A_x = 10^{(1.9 - 0.065\theta)} - 45(m/\theta).$$

FIG. 12 shows the dependency of A_x (the exactly calculated values) upon θ , which is calculated for the rod lens array 2 appropriately selected from Table 1 and the dependency of A_x (the approximate values) upon θ , which is obtained from Equation 24. As can be seen from FIG. 12, the approximate values agree well with the exactly calculated values.

FIG. 13 shows the dependency of $\log_{10}(-A_y)$ upon $(A_x + 2m)$ and that

of $\log_{10}A_z$ upon $(A_x + 2m)$, each of which is calculated for the rod lens arrays 2 appropriately selected from Table 1. The dependency of $\log_{10}(-A_y)$ can be approximated by a linear relationship given by

5 *Eq. 25* $\log_{10}(-A_y) = 2 + 0.1(A_x + 2m)$.

Similarly, the dependency of $\log_{10}A_z$ can be approximated by a linear relationship given by

10 *Eq. 26* $\log_{10}A_z = 2.8 + 0.16(A_x + 2m)$.

The approximate lines of Equations 25 and 26 are illustrated in FIG. 13.

(3) Mean vector B^*

15 The components of the mean vector B^* on the x-axis, y-axis and z-axis can be represented by B_x , B_y and B_z , respectively. That is, the mean vector B^* is expressed by

Eq. 27 $B^* = (B_x, B_y, B_z)$.

20 Since the major vector A^* and the mean vector B^* are perpendicular to each other, B^* can be calculated by determining the coordinates of a point on an ellipse including A^* and B^* , or the like. As shown in FIGS. 14 to 16, each of the three components of B^* , which is calculated for the rod lens arrays 2 appropriately selected from Table 1, can be approximated by a
25 linear relationship with A_x . The approximations as shown in FIGS. 14 to 16 are expressed by

Eq. 28 $B_x = -0.8A_x$,

30 *Eq. 29* $B_y = 100A_x$ and

Eq. 30 $B_z = 1.5A_x$, respectively.

(4) Minor vector C^*

35 First, a plane including the major axis and the mean axis is expressed by

$$\text{Eq. 31 } px + qy + sz = 1$$

where p, q and s are the x-, y-, and z-components of a normal vector to the plane.

- 5 FIGS. 17 to 19 show the dependency of p, q and s upon x_0 , each of which is calculated for the rod lens arrays 2 appropriately selected from Table 1. As shown in FIGS. 17 to 19, p can be approximated by a substantially linear relationship with x_0 , while q and s, though there are variations in their dependency, can be approximated by a constant value.
- 10 The approximations as shown in FIGS. 17 to 19 are expressed by

$$\text{Eq. 32 } p = 0.2x_0 + 0.6,$$

$$\text{Eq. 33 } q = 0.01 \text{ and}$$

$$\text{Eq. 34 } s = 0.0002, \text{ respectively.}$$

The minor vector C^* is a vector having the direction perpendicular to the plane including the major axis and the mean axis. Here, the minor vector C^* is expressed by

$$\text{Eq. 35 } C^* = |C^*| (p', q', s')$$

where p' , q' and s' are the x-, y-, and z-components of a unit vector having the direction of C^* . Therefore, p' , q' and s' satisfy the relationship given by

$$\text{Eq. 36 } p'^2 + q'^2 + s'^2 = 1.$$

Since a vector (p', q', s') is parallel to a vector (p, q, s) , each of the components is expressed by

$$\text{Eq. 37 } p' = p/(p^2 + q^2 + s^2)^{1/2},$$

$$\text{Eq. 38 } q' = q/(p^2 + q^2 + s^2)^{1/2} \text{ and}$$

$$\text{Eq. 39 } s' = s/(p^2 + q^2 + s^2)^{1/2}.$$

FIG. 20 shows the dependency of $|C^*|$ upon $|A^*| \cdot m^2$, which is calculated for the rod lens arrays 2 appropriately selected from Table 1. As shown in FIG. 20, $|C^*|$ and $|A^*| \cdot m^2$ are approximated by a linear relationship. Here, $|A^*|$ is expressed by

$$Eq. 40 \quad |A^*| = (A_x^2 + A_y^2 + A_z^2)^{1/2}.$$

Therefore, the approximation is expressed by

$$Eq. 41 \quad |C^*| = 1.5 \times 10^{-5} |A^*| \cdot m^2.$$

When the radius r_0 of the effective lens portion of each rod lens 1 takes a value other than 0.15 mm, the amount of blurred image caused by various aberrations of the rod lenses 1 increases in proportion to r_0 .

Accordingly, the good image range for the refractive index distribution coefficients h_4 , h_6 , and h_8 determined by Equations 32 to 56 generally shows the following ranges:

for $r_0 = 0.05$ mm, the MTF value of a 72 line-pairs/mm pattern is greater than 50%;

for $r_0 = 0.30$ mm, the MTF value of a 12 line-pairs/mm pattern is greater than 50%; and

for $r_0 = 0.60$ mm, the MTF value of a 6 line-pairs/mm pattern is greater than 50%.

In this embodiment, it is desirable that a parallel plane transparent substrate (cover glass) is arranged so that the manuscript plane 3 is located at the front focal position of the rod lens array 2, as shown in FIG. 21A. This desired configuration allows the manuscript plane 3 to be set at the front focal position by only pressing a manuscript to the surface of the transparent substrate 5. Moreover, it is desirable that the parallel plane transparent substrate (cover glass) 5 is in contact with the lens surface of the rod lens array 2, as shown in FIG. 21B. This can be achieved easily by adjusting the thickness of the transparent substrate (cover glass) 5. This desired configuration can simplify the adjustment of the distance between the rod lens array 2 and the front focal position during fabrication of the optical imaging system, thereby reducing the cost.

In this embodiment, the good image range is determined by Equation 18. However, an even better image range can be achieved by

determining the range with

Eq. 42 $k_A^2 + k_B^2 + k_C^2 \leq 0.7$.

- 5 In this embodiment, the refractive index distribution of the rod lenses 1 is expressed by Equation 29. However, it is not limited to such a distribution. For example, assuming that the secondary refractive index distribution coefficient g , which represents the refractive power near the optical axis, remains the same, the refractive index distribution of the rod lenses 1 can be expressed generally by

Eq. 43 $n(r)^2 = n_0^2 \cdot \{1 - (g \cdot r)^2 + f(r)\}$

where $f(r)$ is a function of r .

- 15 Even if a refractive index distribution is given by the general equation (i.e., Equation 43), a "good image range" for this refractive index distribution can be achieved as long as $f(r)$ satisfies the relationship given by
- 20 Eq. 44 $h_{4A} \cdot (g \cdot r)^4 + h_{6A} \cdot (g \cdot r)^6 + h_{8A} \cdot (g \cdot r)^8 \leq f(r) \leq h_{4B} \cdot (g \cdot r)^4 + h_{6B} \cdot (g \cdot r)^6 + h_{8B} \cdot (g \cdot r)^8$

- for r in the range of $0 \leq r \leq r_0$ with respect to two groups of refractive index distribution coefficients ($n_0, g, h_{4A}, h_{6A}, h_{8A}$) and ($n_0, g, h_{4B}, h_{6B}, h_{8B}$) that are
- 25 in the ranges determined by Equations 17 and 18.

- The invention may be embodied in other forms without departing from the spirit or essential characteristics thereof. The embodiments disclosed in this application are to be considered in all respects as illustrative and not limiting. The scope of the invention is indicated by the
- 30 appended claims rather than by the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are intended to be embraced therein.